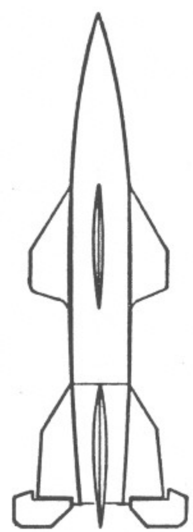
ALSO BY WILLY LEY

Dragons in Amber
The Conquest of Space (with Chesley Bonestell)
The Lungfish, the Dodo, and the Unicorn

Rockets, Missiles, and Space Travel

BY WILLY LEY

L. B. Abreu



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If the spaceship added too much speed to the orbital speed of the earth, it might acquire the tendency to drift across the orbit of Mars instead of just to the orbit. In such a case its own orbit and that of Mars would cross. If it had only enough speed to drift to the orbit of Mars, the two orbits would only touch.

That is the difference between economical and uneconomical orbits. If the orbits of ship and planet *touch,* both move around the sun in precisely the same direction, although not quite with the same speed. But if the orbits of ship and planet *cross,* the ship not only has to change direction but also has to eliminate a greater difference in velocities than in the case of touching orbits, where the difference to be eliminated is not very large as cosmic velocities go. Naturally a much larger amount of fuel would have to be expended in the case of crossing orbits and, since this fuel had to be lifted from earth first, it does mean *much* more fuel—a much larger mass-ratio—at the beginning of the trip. It is easy to see why having the orbits touch is more economical than having them cross.

One cannot ask at this point whether such a thing could be done or not. The possibility or impossibility, the improbability or probability, if you prefer, depends mainly on the figures which result from definite calculations. There is no way of passing judgment until we know the figures for the velocities (or rather their changes) and the masses involved.

We can now proceed to some figures from which that answer may be derived. This exposition of the problem was given in 1928 by the late Dr. Walter Hohmann in my book *Die Möglichkeit der Weltraumfahrt.* I am not going to repeat Dr. Hohmann's calculations, but only state the problems and give his results.

All the Hohmann orbits, as they have come to be called, are, as is natural, Keplerian ellipses which lie in the plane of the ecliptic (the earth's orbit), and which follow the general rotation of the solar system and touch or cross at least two planetary orbits.

I have inserted the phrase "follow the general rotation of the solar system" advisedly. Naturally one can imagine and calculate a Keplerian ellipse pointing in the opposite direction, but this would be a noneconomical orbit *par excellence.* It would mean the acquisition of more than the orbital velocity of the earth *against* the orbital velocity of the earth and it would again mean reducing all this velocity to zero and acquiring a high velocity in the opposite direction to catch up with the orbital velocity of the target planet, all this leading up to a landing against that planet's gravitation. This is something that clearly cannot be done, and

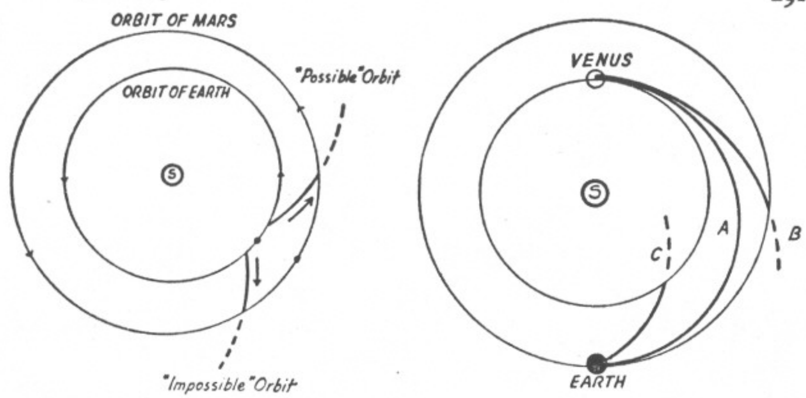

Fig. 47. Hohmann orbits.

Left: A "possible" orbit, which follows the general rotation of the solar system, and an opposing orbit, labeled "impossible" because of the fantastic fuel expenditure it would require.

Right: Three "possible" orbits of which the one labeled A takes the longest time but also involves the smallest fuel expenditure.

orbits which do not follow the general rotation of the solar system are therefore ruled out as "impossible orbits" (Fig. 47, left).

As regards the "possible" orbits, Dr. Hohmann simplified the calculations somewhat by making two assumptions about the orbits of the planets. We know that they are elliptical but to such a small extent that they look like circles on a small drawing. And we also know that they are tilted against the plane of the earth's orbit to a very slight degree. Dr. Hohmann made the two assumptions that the orbits of the inner planets lie precisely in the same plane and that they are circular. The latter assumption has the purpose of getting rid of the complication that would otherwise arise from the fact that the planets travel somewhat faster at perihelion than at aphelion. He assumed that the *mean* orbital velocity of a planet held true for every point of the orbit. Expressed in slightly more technical language, he assumed that the radius vector does not only sweep over equal areas during equal time intervals, but also describes equal angles. The difference between this simplified picture and actual conditions is such that it would spell doom for a spaceship whose navigator lightens his duties in a similar manner. But it is not large enough to change the figures to an important extent and at present we only want some general figures which can serve as a basis for conclusions about the probability of the whole venture.

Dr. Hohmann's first example is a trip to Venus. He started out by drawing five possible orbits called A, B, C, D, and E. Orbit A *touches* the orbits of both Venus and the earth; orbit B crosses the orbit of earth but touches the orbit of Venus; while orbit C touches the orbit of earth but crosses that of Venus. Orbit D is similar to orbit C, only less abrupt, while orbit E is of the same type as orbit B. The spaceship was supposed to arrive at Venus and adjust its velocity, but not to land. Its final weight, at that moment, was assumed to be 6 tons, including three passengers. The allowance for the passengers during the trip had been 10 kilograms or 22 pounds per man per day which is at least ample (Fig. 47, right).

The results are condensed in the following table which should be studied carefully:

ORBIT USED	DURATION OF TRIP (DAYS)	ORIGINAL MASS OF SHIP IN TONS * AT EXHAUST VELOCITIES (M/SEC)			
		3000	*4000*	*5000*	*10,000*
A	146	49	34	27	18
B	75	530	200	104	31
C	69	5,900	1,060	417	60
D	109	141	70	48	22
E	102	172	83	55	24

* The term "ton" always means 1000 kg or 2200 lb.

This first table settles one point: only A orbits can be considered at all. Any orbit that crosses a planetary orbit and involves a change of direction has to be ruled out almost as strictly as an orbit that does not follow the general rotation of the solar system.

But those figures must not be misunderstood. They do not mean that a 6-ton ship, having an exhaust velocity of 5000 meters per second, would need 21 tons of fuel to get to Venus in 146 days. Or that, with 3000 meters per second of exhaust velocity, it would need 43 tons of fuel for the trip. If that were the whole story, we might seriously think about the construction of a spaceship some time next week. These figures merely express the tribute that has to be paid to the sun if one moves a spaceship from the orbit of earth to the orbit of Venus and regulates the velocities so that they agree with those of the planets at both ends. So far the two planets have been treated as if they had no gravitational power of their own. The figures in the table do *not* include the departure from earth. Nor has anything been said about the return. So far the only thing that can be kept in mind as definite is the duration of the trip: 146 days. Similarly the duration of the trip to Mars along an A orbit would require 258 days.

Before we try to establish the true mass-ratios required—the mass-

ratios which include departure from the earth, landing, and similar problems—we have to find out the true duration of the trip, which means the duration of a *round trip*. It is not simply twice 146 days in the case of Venus or twice 258 days in the case of Mars. The planets move.

Supposing we have completed an A orbit to Mars and have, for some reason, decided not to land but to return at once. The thing to do, it would seem, would be not to adjust the ship's velocity to the velocity of Mars at all but simply to stay in the same orbit. Without the expenditure of any fuel, the orbit would carry us back without fail, back to the orbit of the earth. But the earth itself would be elsewhere.

When we departed from the earth, the slower Mars was far ahead. The time of departure was calculated in such a manner that the ship would catch up with the planet. But during the 258 days the relatively fast earth raced ahead. At the end of the trip the earth would be far from the point touched by the return orbit. There is no other way out but to linger on or near Mars until Mars is ahead of the earth, which means, of course, until the earth is behind by having completed more than one full revolution around the sun. This waiting period is unfortunately rather long; it amounts to 455 days. Thus the round trip to Mars requires 258 + 455 + 258 = 971 days or about two years and eight months (Fig. 48).

On a round trip to Venus conditions are reversed since Venus is faster than the earth, but the net result is again a waiting period on or near Venus. It is even a little longer: 470 days. The duration of the whole round trip is, consequently, 146 + 470 + 146 = 762 days, or two years and a month. The trip is seven months shorter than the round trip to Mars, simply because of the shorter duration of the trips themselves, even though the waiting period is two weeks longer.

Now for the mass-ratios required. The table of mass-ratios for the departure from earth looks like this:

EXHAUST VELOCITY (M/SEC)	MASS-RATIO
3,000	95
4,000	30
5,000	15
10,000	4

Air resistance and mild acceleration for the sake of the pilot are included in this table. These figures are not tons, they are ratios. If you would like to find out for yourself what initial masses you have to count on for going to Venus, you can make a choice of exhaust velocity, pick the proper figure for the Venus trip from the table on page 292,

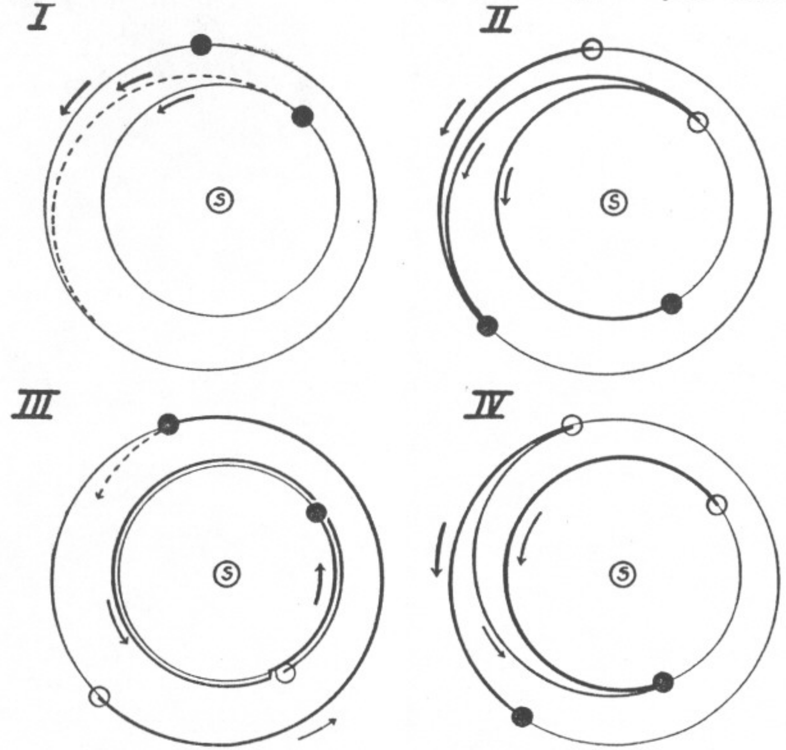

Fig. 48. A trip to Mars and back. I. Position of the two planets (black circles) at beginning of trip, the broken line showing the orbit to be traveled by the spaceship. II. Position at the moment of arrival on Mars, black circles; previous position, white circles. III. Position at date of departure from Mars. Mars has completed the whole journey from white to black circle while the earth has traveled around the sun in its orbit almost one and a quarter times. IV. Position at date of spaceship's arrival on earth.

and multiply it by the figure for the same exhaust velocity in the table on page 293. This is not the proper way of making the calculation and it is impossibly bad from the point of view of a mathematician, but it will give you approximate results.

Things begin to look very dark now. The mass-ratios become enormous. And with all that expenditure you just manage to get off the earth, drift to Venus, adjust your velocity there, and make a landing of the type indicated in Fig. 51 and described on page 303.

The procedure of the trip, as outlined by Hohmann, would be to ascend from the earth vertically in an arbitrary direction, until the ship

is 500,000 miles from the surface. At this distance the gravitational field of the earth can be neglected. The ship is now independent of the earth, but still has the same orbital velocity as the earth. Now change the orbital velocity of the ship, a change of less than 2 miles per second. The ship is now on its way, drifting inward in the solar system along an A orbit. During the initial ascent, which takes a few days, the rocket motors work for about 8 minutes; in order to change the orbital velocity they work for another 2 minutes. From then on they are quiet until the orbit of Venus and Venus itself are reached. But the ship, during the inward drift, which is really a fall toward the sun, has gathered speed; it is now somewhat faster than Venus. That difference has to be adjusted; Venus and the ship are then really in the same orbit, moving with the same velocity. This is, of course, an unstable condition. The gravity of the planet will draw the ship down ("down" as seen from the planet) and the landing maneuver will have to begin. The landing maneuver is again designed to kill speed, but this time it is the speed resulting from the attraction of the planet. All this holds true for a trip to Mars too, except that the landing would require the expenditure of fuel to kill the falling speed of the ship.

Here are the figures I promised, all neatly condensed into one table. They are valid for a 6-ton ship with three passengers, each of whom has a food-water-oxygen allowance of 22 pounds per day.

EXHAUST VELOCITY AVAILABLE (M/SEC)	INITIAL MASS OF SHIP REQUIRED (TONS)			
	TRIP		RETURN (INDEPENDENT)	
	TO VENUS	TO MARS	FROM VENUS	FROM MARS
3,000	4,680	29,500	2,510	382
4,000	1,020	4,180	690	182
5,000	410	1,260	276	110
10,000	73	135	64	41

It can be seen that it is, comparatively speaking, easier to go to Venus, but it is easier to return from Mars. The figures really are not bearable except for those which refer to the 10,000-meter-per-second exhaust velocity which we don't know how to achieve at the present moment. And there is another unpleasantness in the table; the figures for the return trip are for an *independent return,* which means that the fuel supply for the return trip is not carried along but is taken on (or manufactured) on the other planet. The idea of manufacturing the fuel for the return trip is not quite as farfetched as it may seem; the "raw" fuel may be simply water. And the waiting period does provide time.

The first trip, of course, would not be one with a landing on the planet, especially since it is likely that all the information needed for future plans can be gathered by way of prolonged close observation of the planet. This then would be a round trip during which the waiting period is spent circling the planet.

The mass-ratios for such a venture, again for a 6-ton ship with the usual assumptions, are given in the following table:

	INITIAL MASS OF SHIP (TONS)		
EXHAUST VELOCITY AVAILABLE (M/SEC)	EARTH-MARS-EARTH, WITH CIRCLING OF PLANET	EARTH-VENUS-EARTH, WITH CIRCLING OF PLANET	SPECIAL ROUND TRIP
3,000	65,500	40,000	46,300
4,000	9,400	6,330	6,700
5,000	3,100	2,160	2,160
10,000	356	284	244

Again only the figures in the bottom line look bearable, but it is always amazing to see how just a slight increase in exhaust velocity slashes away at the mass-ratio requirements.

The figures in the last column, labeled "special round trip," need some explanation and a diagram (Fig. 49). It is assumed here that the ship goes to Mars, but that it does not land. But neither does it spend the whole waiting period circling Mars. After several weeks, say, the pilot decreases the orbital velocity and begins to drift inward along an A orbit which leads directly from the orbit of Mars to that of Venus; earth's orbit is naturally crossed on the way, but the earth is nowhere in sight. Venus, however, is at the meeting place and is circled for a while. The orbital speed of the ship is then increased again so that it is flung into an A orbit to the earth, reaching earth one and a half years after the original departure and having accomplished a survey of both planets in a shorter time and with slightly less fuel expenditure than that required for a no-landing trip to Mars alone.

This survey of Hohmann's excellent early work—it may be well to remember that Hohmann worked out all these things when the most powerful rockets on record were still the old Congreve war rockets—has shown that the problem of interplanetary travel lends itself to a cool mathematical investigation. It has also shown that the concept of trips to the two neighboring planets completely lacks the dare-devil hit-or-miss spirit with which it is imbued in stories of that kind. Actually that concept is a cold-blooded piece of planning, based on well-established natural laws. Another result which has emerged, so to speak in passing, is that the question of time is not of the order of that famous schoolbook example of the cannon ball which, "if it could be fired at the sun would need

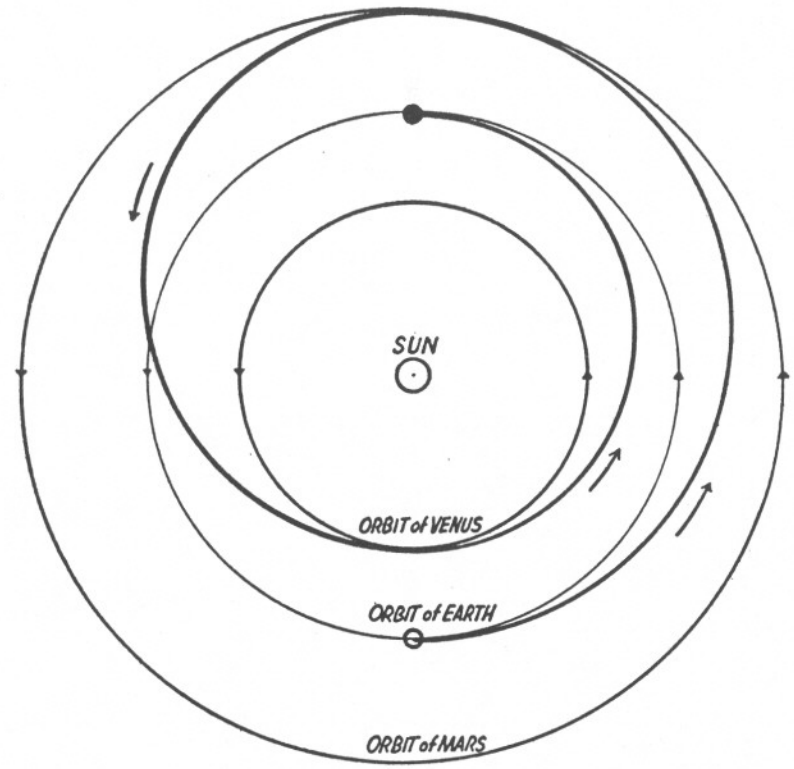

Fig. 49. The so-called Hohmann round trip.

two centuries to get there." The trips are of the order of the average duration of extended expeditions on earth.

All this is very gratifying indeed, and it is not the fault of the investigator that the mass-ratios turned out to be on the impossible side most of the time. Only those where an exhaust velocity of 10,000 meters per second was assumed looked at all reasonable in some cases.

The need for a fuel with such a high exhaust velocity was also confirmed by Count Guido von Pirquet, a member of an old noble family in Austria, a family which is also noted in the annals of science. His brother was one of Vienna's foremost and most famous pediatricians. When Guido von Pirquet became interested in space travel he attacked the new field with much skill and great enthusiasm. But he made his living as a practical engineer and that colored his approach.

Other authors had bemoaned the high initial mass of a spaceship, presumably thinking "so-and-so many dollars per ton." Count von Pirquet perceived another impossibility connected with such a high mass, an engineering impossibility. In the first place he pointed out that a manned ship cannot be operated like a straight rocket. We have seen that the acceleration goes up because the rocket's weight diminishes steadily while the thrust remains about the same. For research rockets this is fine, but for a manned ship such steadily increasing acceleration won't do. An acceleration which starts out with, say, 3 *g* and goes up to 25 *g* is fine for the performance of the ship but is likely to kill off the crew. Consequently in a manned ship the thrust would have to be adjusted to the diminishing mass of the ship. That, from an engineering point of view, is difficult and would involve inefficient operation, unless the ship operates on a bank of motors which can be cut off one by one. In 1928, when von Pirquet began publishing his studies, that problem looked far worse than it does now. Nor was it the problem which worried von Pirquet most. What did worry him was, on the contrary, the problem of fuel supply for the first few seconds of ascent. At take-off the ship is enormously heavy. Consequently the amount of fuel to be burned to lift it off the ground while it is so heavy is simply fantastic. He assumed an exhaust velocity of 4000 meters per second, the figure used by Oberth for the calculation of the moon ship, and then calculated the weight of a Mars ship on that basis. After that he tried to determine the amount of fuel required for the first second of take-off, to lift the Mars ship off the ground.

One hundred and five tons for the first second!

It is no consolation to know that it will be much less only half a minute later. Even if this fuel expenditure held true for only a single second, the motors would have to handle that volume. To show what size that would imply, von Pirquet calculated a rocket motor for a fuel consumption of 105 tons per second. The narrowest part of the exhaust nozzle would still have to have an area of about 1600 square feet and the area of the mouth of the exhaust nozzle about 16,000 square feet. Even though in reality it would not be a single motor this simply would be too much.

The example not only proved that it was impossible to build interplanetary ships with the mass-ratios necessary to make direct trips, it showed in addition that such a ship could not lift off, even if it could be built. With an exhaust velocity of 4000 or even 5000 meters per second it simply cannot be done at all. With 10,000 meters per second it would be something else again, and Dr. Hohmann, when he used this figure for purposes of comparison, may have thought vaguely of mon-atomic hydrogen as a fuel. It is the figure one could expect from mon-atomic hydrogen, provided it could be manufactured in quantity and could be used.

The name of that substance is somewhat misleading; it has nothing to do with atomic energy. But one might hope for an exhaust velocity of 10,000 meters per second from the use of real atomic energy, the fission of U-235 atoms, working on a "reaction mass" of some kind, possibly liquid hydrogen, preferably water. There is enough energy available that 10,000 meters per second does not seem at all unreasonable. And if somebody hopes for 20,000 meters per second there is little reason to contradict him, except for saying that that might take a little while longer.

In order to show what such high exhaust velocities would do to the mass-ratios we have to go back to Oberth's moon ship for an example and a method. It may have been noticed that Professor Oberth and Dr. Hohmann used different approaches in arriving at their mass-ratios. Oberth's method consisted in ascertaining the magnitudes of the changes in velocity required for the various maneuvers. These changes are then added up, so that you get a figure for the whole trip. The *sum* of all the changes in velocity that have to be accomplished by rocket power is the "ideal velocity" for the planned trip, like that figure of 19,310 meters per second for a trip to the moon with landing on the moon and subsequent return. The mass-ratio for the whole trip is then found very easily by calculating the mass-ratio for the "ideal velocity" with a given exhaust velocity.

Dr. Hohmann established the mass-ratio for each maneuver separately; the total mass-ratio requirement for a planned trip is the *product* of multiplication of the various mass-ratios with each other. Each of these two methods has advantages and disadvantages of its own: Hohmann's method is more graphic; Oberth's is simpler in operation and a handier tool. I am going to follow Oberth's method from now on, partly because of its convenience, partly because it also has to do with a fuel-saving method of leaving the earth.

In rocket literature that fuel-saving method goes under the clumsy but appropriate name of "the problem of the condensation of power application." Hohmann's hypothetical pilot, you remember, first left earth in an arbitrary direction to become virtually free of the gravitational attraction of the home planet. Then he changed the orbital velocity of the ship, which was still the same as earth's, with respect to the sun, and proceeded on his way.

It is obvious, even without a detailed study, that a combination of ascent from the earth and change of orbital velocity, accomplished, one